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6. AUTHORS
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7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
New York University
Office of Sponsored Programs
New York University
New York, NY 10003 -

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14. ABSTRACT
This research project explored new methods to coherently control magnetization dynamics in nanostructures based on a recently discovered strong and short-range quantum mechanical interaction between a spin-current and background magnetization—known as spin-transfer. This was accomplished through the fabrication and study of prototype spin-transfer devices. Specifically, we pursued the following approaches: (1) Fabrication of magnetic devices in which the magnetic anisotropy is controlled through oriented, layered or epitaxial film growth; (2)

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UU	UU	UU	UU		Andrew Kent
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Report Title

Final Report: Ultrafast Magnetoelectronic Devices

ABSTRACT

This research project explored new methods to coherently control magnetization dynamics in nanostructures based on a recently discovered strong and short-range quantum mechanical interaction between a spin-current and background magnetization—known as spin-transfer. This was accomplished through the fabrication and study of prototype spin-transfer devices. Specifically, we pursued the following approaches: (1) Fabrication of magnetic devices in which the magnetic anisotropy is controlled through oriented, layered or epitaxial film growth; (2) Realization of magnetic devices that combine low moment and high moment materials; and (3) High speed electrical measurements of magnetization switching and precession.

We had a number of significant experimental results that have become benchmarks in the field:
1. We demonstrated spin-transfer switching with current pulses shorter than 300 psec. We also studied how the switching threshold depends on current pulse amplitude and duration for pulses between 100 ps and 1 s in duration.
2. We developed an all electrical method to study magnetization relaxation in a nanomagnet with 50 ps time relaxation and used this method to determine the relaxation time of a nanomagnet in a prototype spin-transfer device.
3. We explored highly non-linear magnetization dynamics excited by microwave spin-currents.
4. We also characterized transition metal multilayer and alloy thin films of interest in spin-transfer torque devices using broadband (1-50 GHz) ferromagnetic resonance spectroscopy.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper
2012/03/22 1! 13	J.-M. Beaujour, D. Ravelosona, I. Tudosa, E. E. Fullerton, A. D. Kent. Ferromagnetic resonance linewidth in ultrathin films with perpendicular magnetic anisotropy, Physical Review B, (11 2009): 0. doi: 10.1103/PhysRevB.80.180415
2012/03/22 1! 12	S. Girod, M. Gottwald, S. Andrieu, S. Mangin, J. McCord, Eric E. Fullerton, J.-M. L. Beaujour, B. J. Krishnatreya, A. D. Kent. Strong perpendicular magnetic anisotropy in Ni/Co(111) single crystal superlattices, Applied Physics Letters, (06 2009): 0. doi: 10.1063/1.3160541
2012/03/22 1· 11	W. Chen, G. de Loubens, J.-M. L. Beaujour, A. D. Kent, J. Z. Sun. Finite size effects on spin-torque driven ferromagnetic resonance in spin valves with a Co?Ni synthetic free layer, Journal of Applied Physics, (02 2008): 0. doi: 10.1063/1.2832671
2012/03/22 1· 10	J.-M. L. Beaujour, G. de Loubens, W. Chen, A. D. Kent, J. Z. Sun. Spin-torque driven ferromagnetic resonance of Co?Ni synthetic layers in spin valves, Applied Physics Letters, (01 2008): 0. doi: 10.1063/1.2827570
2012/03/21 1! 8	Andrew D. Kent. Spintronics: Perpendicular all the way, Nature Materials, (09 2010): 0. doi: 10.1038/nmat2844
2012/03/21 1' 6	J.-M. L. Beaujour, A. D. Kent, D. Ravelosona, I. Tudosa, E. E. Fullerton. Ferromagnetic resonance study of Co/Pd/Co/Ni multilayers with perpendicular anisotropy irradiated with helium ions, Journal of Applied Physics, (02 2011): 0. doi: 10.1063/1.3544474
2012/03/21 1' 5	D. Bedau, H. Liu, J. Z. Sun, J. A. Katine, E. E. Fullerton, S. Mangin, A. D. Kent. Spin-transfer pulse switching: From the dynamic to the thermally activated regime, Applied Physics Letters, (12 2010): 0. doi: 10.1063/1.3532960
2012/03/21 1' 4	D. Bedau, H. Liu, J.-J. Bouzaglou, A. D. Kent, J. Z. Sun, J. A. Katine, E. E. Fullerton, S. Mangin. Ultrafast spin-transfer switching in spin valve nanopillars with perpendicular anisotropy, Applied Physics Letters, (01 2010): 0. doi: 10.1063/1.3284515
2012/03/21 1' 3	W. Chen, G. de Loubens, J.-M. L. Beaujour, J. Z. Sun, A. D. Kent. Spin-torque driven ferromagnetic resonance in a nonlinear regime, Applied Physics Letters, (10 2009): 0. doi: 10.1063/1.3254242
2012/03/21 1(2	Andrew D. Kent, Daniel L. Stein. Annular Spin-Transfer Memory Element, IEEE Transactions on Nanotechnology, (01 2011): 0. doi: 10.1109/TNANO.2009.2033598
2012/03/21 1(1	J.-M. L. Beaujour, A. D. Kent, D. W. Abraham, J. Z. Sun. Ferromagnetic resonance study of polycrystalline Fe[sub 1-x]V[sub x] alloy thin films, Journal of Applied Physics, (02 2008): 0. doi: 10.1063/1.2830648

TOTAL: 11

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

A. D. Kent, Invited Talk: “Spin-Transfer Driven Magnetization Dynamics and Relaxation in Nanopillars,” M-SNOWS 2012, École de Physique, Les Houches, France, February 2012

A. D. Kent, Invited Talk: “Ultra-fast Spin Transfer Driven Switching” at the International Workshop on Spin Transfer January 19, University of Nancy, Nancy, France

Huanlong Liu (graduate student), Invited Talk: “Spin-transfer pulse switching in all perpendicular spin-valve nanopillars,” 56th Annual Conference on Magnetism and Magnetic Materials, MMM 2011, Scottsdale Arizona

Huanlong Liu (graduate student), Talk: “Equilibration in All-Perpendicular Spin Valves Subject to Short Current Pulses,” 2011 APS March Meeting, Dallas, Texas?

Daniel Bedau (postdoc), Invited Talk, "Ultrafast Spin-Transfer Switching in All- Perpendicular Spin Valve Nanopillars," 11th Joint MMM–Intermag Conference 18–22 January 2010, Washington, DC, USA

Huanlong Liu (graduate student), "Switching and Equilibration in All-Perpendicular Spin Valves Subject to Short Current Pulses," 11th Joint MMM–Intermag Conference
18–22 January 2010, Washington, DC, USA

Number of Presentations: 6.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
2012/03/21 1!	9	Arne Brataas , Andrew D. Kent, Hideo Ohno. Current-Induced Torques in Magnetic Materials, Nature Materials (11 2011)
2012/03/21 1!	7	H. Liu, D. Bedau, J. Z. Sun, S. Mangin, E. E. Fullerton, J. A. Katine, A. D. Kent. Time-Resolved Magnetic Relaxation of a Nanomagnet on Subnanosecond Time Scales, Phys Rev Lett (submitted) (02 2012)

TOTAL: 2

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

High Speed Low Power Magnetic Devices Based on Current Induced Spin-Momentum Transfer

Patents Awarded

High Speed Low Power Magnetic Devices Based on Current Induced Spin-Momentum Transfer, US 7,911,832 B2

Awards

Invited Professor, Institut Jean Lamour, CNRS – Nancy Université, BP 239, F-54506 Vandoeuvre, France, Sept. 2008-August 2011

Invited Professor, Institut d'Electronique Fondamentale (IEF), Université Paris Sud-Bat 220, 91405 Orsay Cedex, France, Sept. 2009-August 2011

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Wenyu Chen	0.25	
Huanlong Liu	0.50	
FTE Equivalent:	**0.75**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Daniel Bedau	0.20
Jean-Marc Beaujour	0.10
FTE Equivalent:	**0.30**
Total Number:	**2**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Andrew Kent	0.11	
FTE Equivalent:	**0.11**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Matt Reimer	0.00	Physics
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	1.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):	1.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME	
Wenyu Chen	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

5 **High Speed Low Power Magnetic Devices Based on Current Induced Spin-Momentum Transfer**

Patent Filed in US? (5d-1) Y

Patent Filed in Foreign Countries? (5d-2) Y

Was the assignment forwarded to the contracting officer? (5e) Y

Foreign Countries of application (5g-2): EU, Japan, Singapore, Candana, Korea, China

5a: Jean-Marc Beaujour

5f-1a: New York University

5f-c:

Elmhurst NY

5a: Daniel Stein

5f-1a: New York University

5f-c:

New York NY

Scientific Progress

See the attached report.

Technology Transfer

ARO Final Report

Report Type: Interim Progress Report
Proposal Number: 52906EL
Agreement Number: W911NF0710643
Proposal Title: Electronics: Ultra-Fast Magnetoelectronic Devices
Report Period Begin Date: October 1, 2007
Report Period End Date: September 30, 2011

Organization Information
New York University
Office of Sponsored Programs
New York, NY 10003

Author: Andrew D. Kent

Subject Terms/Keywords:
Magnetization dynamics, spin transfer, spin-transfer MRAM, spin transfer oscillators, mixers, perpendicular anisotropy

Abstract:

This research project explored new methods to coherently control magnetization dynamics in nanostructures based on a recently discovered strong and short-range quantum mechanical interaction between a spin-current and background magnetization—known as spin-transfer. This was accomplished through the fabrication and study of prototype spin-transfer devices. Specifically, we pursued the following approaches: (1) Fabrication of magnetic devices in which the magnetic anisotropy is controlled through oriented, layered or epitaxial film growth; (2) Realization of magnetic devices that combine low moment and high moment materials; (3) High speed electrical measurements of magnetization switching and precession.

In this we project we had a number of significant experimental results that have become benchmarks in the field:

1. We demonstrated spin-transfer switching with current pulses shorter than 300 ps. We also studied how the switching threshold depends on current pulse amplitude and duration for pulses between 100 ps and 1 s duration.
2. We developed an all electrical method to study magnetization relaxation in a nanomagnet with 50 ps time relaxation and used this method to determine the relaxation time of a nanomagnet in a prototype spin-transfer device.
3. We explored highly non-linear dynamics excited by microwave spin-currents.
4. We also characterized thin films of interest in spin-transfer torque devices using broadband (1-50 GHz) ferromagnetic resonance spectroscopy.

Scientific Progress and Accomplishments (over entire period of the contract)

This research program investigated devices that have the capability of exhibiting ultra-high speed switching of the magnetization and high frequency magnetization precession. This was accomplished through the fabrication and study of prototype spin-transfer devices. Specifically, we are pursuing the following approaches:

(1) Fabrication of magnetic devices in which the magnetic anisotropy is controlled through oriented, layered or epitaxial film growth;
(2) Realization of magnetic devices that combine low moment and high moment materials;
(3) High speed electrical measurements of magnetization switching and precession

We have made progress on all the items listed above: (1) We realized magnetic multilayers with strong perpendicular anisotropy that function as the spin-polarizing layer in a spin-transfer device. (2) We fabricated thin films of $Fe_{1-x}V_x$ with variable magnetization density and low Gilbert damping. These materials may be used to fabricate magnetic devices that combine low moment and high moment materials. Their low Gilbert damping may prove to be effective in lowering the threshold currents for switching and magnetization precession. (3) We have conducted studies of switching with short current pulses in all-perpendicularly magnetized spin-valve nanopillars. Also on item (3) we have installed, fully automated and commissioned a new high speed measurement station that permits studies of high speed magnetization switching with a high speed pulse generator in combination a real-time high bandwidth oscilloscope. (4) We have conducted and analyzed spin-torque driven ferromagnetic resonance experiments conducted in a highly nonlinear regime of magnetization dynamics.

In this period grant (October 1, 2007 to December 31, 2011) we published 12 articles and have one manuscript submitted and under review. A majority of the articles were in high impact journals such as Nature Materials (2 articles) and Applied Physics Letters (5 articles). We also submitted and published a patent, which was licensed by a start-up company, Spin-Transfer Technologies Inc. Here we summarize the key scientific results during the entire period of the project.

FMR Measurements of Confined Magnetic Layers in Nanopillar Junctions: Spin-torque driven ferromagnetic resonance (ST-FMR) was used to study thin Co/Ni synthetic layers with perpendicular anisotropy confined in spin-valve based nanojunctions. Field swept ST-FMR measurements were conducted with a magnetic field applied perpendicular to the layer surface. The resonance lines were measured under low amplitude rf excitation, from 1 to 20 GHz. These results were compared with those obtained using conventional rf field driven FMR on extended films with the same Co/Ni layer structure. The layers confined in spin valves have a lower resonance field, a narrower resonance linewidth and approximately the same linewidth vs. frequency slope, implying the same damping parameter. The critical current for magnetic excitations was determined from measurements of the resonance linewidth vs. dc current and is in accord

with the one determined from I-V measurements. Published in Applied Physics Letters **92**, 012507 (2008).

Finite size effects in FMR of Confined Magnetic Layers in Nanopillar Junctions: Spin-torque driven ferromagnetic resonance (ST-FMR) is used to study the magnetic excitations in a Co/Ni synthetic layer confined in nanojunctions. Field swept ST-FMR measurements were conducted with a magnetic field applied perpendicular to the layer surface. The resonance lines were measured under low amplitude excitation in a linear response regime. The resulting resonance fields were compared with those obtained using conventional rf field driven FMR on extended films with the same Co/Ni layer structure. A lower resonance field is found in confined structures. The effect of both dipolar fields acting on the Co/Ni layer emanating from other magnetic layers in the device and finite size effects on the spin wave spectrum, were considered in understanding the `blue' shift of the resonance. Published in Journal of Applied Physics **103**, 07A502 (2008).

Ferromagnetic Resonance Study of Polycrystalline FeV Alloy Films: Ferromagnetic resonance was used to study the magnetic properties and magnetization dynamics of polycrystalline $Fe_{1-x}V_x$ alloy films with $0<x<0.7$. Films were produced by co-sputtering from separate Fe and V targets, leading to a composition gradient across a Si substrate. FMR studies were conducted at room temperature with a broadband coplanar waveguide at frequencies up to 50 GHz using the flip-chip method. The effective demagnetization field $\mu_0 M_{eff}$ and the Gilbert damping parameter have been determined as a function of V concentration. The results were compared to those of epitaxial FeV films. Published in Journal of Applied Physics **103**, 07B519 (2008).

Strong perpendicular magnetic anisotropy in Ni/Co(111) single crystal superlattices: Single crystal Ni/Co(111) superlattices have been grown by molecular beam epitaxy. The Ni thickness is 3 ML whereas the Co thickness varies from 0.2 to 4 ML. The superlattices were studied using magnetometry and ferromagnetic resonance spectroscopy and they all exhibit strong perpendicular to the plane magnetic anisotropy. The maximum magnetocrystalline anisotropy is obtained for one cobalt monolayer. Kerr microscopy measurements show the variation of domain pattern as the Co layer thickness changes. Published in Applied Physics Letters **94**, 262504 (2009).

Annual spin-transfer memory element: An annular magnetic memory that uses a spin-polarized current to switch the magnetization direction or helicity of a magnetic region is proposed. The device has magnetic materials in the shape of a ring (1 to 5 nm in thickness, 20 to 250 nm in mean radius and 8 to 100 nm in width), comprising a reference magnetic layer with a fixed magnetic helicity and a free magnetic layer with a changeable magnetic helicity. These are separated by a thin non-magnetic layer. Information is written using a current flowing perpendicular to the layers, inducing a spin-transfer torque that alters the magnetic state of the free layer. The resistance, which depends on the magnetic state of the device, is used to read out the stored information. This device offers several important advantages compared to conventional spin-transfer magnetic random access memory (MRAM) devices. First, the ring geometry offers stable magnetization states, which are, nonetheless, easily altered with short current pulses.

Second, the ring geometry naturally solves a major challenge of spin-transfer devices: writing requires relatively high currents and a low impedance circuit, whereas readout demands a larger impedance and magnetoresistance. The annular device accommodates these conflicting requirements by performing reading and writing operations at separate read and write contacts placed at different locations on the ring. Published in IEEE Transactions on Nanotechnology **10**, 129 (2011). A US patent application on this device was filed June 2009 and granted March 2012, US 7,911,832 B2

Ferromagnetic resonance linewidth in ultrathin films with perpendicular magnetic anisotropy: Transition metal ferromagnetic films with perpendicular magnetic anisotropy (PMA) have ferromagnetic resonance (FMR) linewidths that are one order of magnitude larger than soft magnetic materials, such as pure iron (Fe) and permalloy (NiFe) thin films. A broadband FMR setup has been used to investigate the origin of the enhanced linewidth in Ni|Co multilayer films with PMA. The FMR linewidth depends linearly on frequency for perpendicular applied fields and increases significantly when the magnetization is rotated into the film plane. Irradiation of the film with Helium ions is used to reduce the PMA and the distribution of PMA parameters. This leads to a great reduction of the FMR linewidth for in-plane magnetization. These results suggest that fluctuations in the PMA lead to a large two-magnon contribution to the linewidth for in-plane magnetization and establish that the Gilbert damping is enhanced in such materials α=0.04, compared to $\alpha\approx$0.002 for pure Fe). Published in Physical Review B Rapid Communications **80**, 180415(R) (2009).

Spin-torque driven ferromagnetic resonance in a nonlinear regime: Spin-valve based nanojunctions incorporating Co|Ni multilayer's with perpendicular anisotropy were used to study spin-torque driven ferromagnetic resonance (ST-FMR) in a nonlinear regime. Perpendicular field swept resonance lines were measured under large amplitude microwave current excitation, which produces large angle precession of the Co$|$Ni layer magnetization. With increasing rf power the resonance lines broaden and become asymmetric, with their peak shifting to lower applied field. A step jump in ST-FMR voltage signal was also observed at high powers. The results are discussed in in terms of the foldover effect of a forced non-linear. Published in Applied Physics Letters **95**, 172513 (2009).

Time-Resolved Magnetic Relaxation of a Nanomagnet on Subnanosecond Time Scales: In this article we present a two-current-pulse temporal correlation experiment to study the intrinsic subnanosecond nonequilibrium magnetic dynamics of a nanomagnet during and following a pulse excitation. This method is applied to a model spin-transfer system, a spin valve nanopillar with perpendicular magnetic anisotropy. Two-pulses separated by a short delay (< 500 ps) are shown to lead to the same switching probability as a single pulse with a duration that depends on the delay. This demonstrates a remarkable symmetry between magnetic excitation and relaxation, consistent with a simple finite temperature Fokker-Planck macrospin model of the dynamics. Submitted for publication to Physical Review Letters.